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CPT site characterization for seismic hazards in the New Madrid seismic zone

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Abstract

A series of cone penetration tests (CPTs) were conducted in the vicinity of the New Madrid seismic zone in central USA for quantifying seismic hazards, obtaining geotechnical soil properties, and conducting studies at liquefaction sites related to the 1811–1812 and prehistoric New Madrid earthquakes. The seismic piezocone provides four independent measurements for delineating the stratigraphy, liquefaction potential, and site amplification parameters. At the same location, two independent assessments of soil liquefaction susceptibility can be made using both the normalized tip resistance (q_{c1N}) and shear wave velocity (V_{s1}). In lieu of traditional deterministic approaches, the CPT data can be processed using probability curves to assess the level and likelihood of future liquefaction occurrence.

Keywords: Cone-penetration test; In situ tests; Site characterization; Liquefaction; Paleoliquefaction; Porewater pressures; Seismic hazard; Shear waves

1. Introduction

Hundreds of earthquake events occurred in the New Madrid seismic zone (NMSZ) during December 1811 and February 1812, with the three largest events estimated to have moment magnitudes of 7.9, 7.6, and 8.0 [1]. This historic earthquake sequence raised questions regarding the earthquake potential of the seismic zone. Clearly a repeat of such a New Madrid event today would be very damaging to the infrastructure of the central US, as well as a significant threat to the large population who live and work in this region. In recent years, paleoseismology studies of earthquake-induced liquefaction features have provided valuable data regarding the earthquake history and potential of the NMSZ [2,3]. Recent research in Japan and western USA, where earthquakes occur more frequently, notes the important finding that sites that experience liquefaction will likely liquefy again during events of similar magnitude [4,5]. Therefore, it is desirable to have a reliable and expedient means to evaluate the liquefaction potential over large developed urban and suburban regions. Here, in particular, the efforts are to quantify the seismic hazards related to liquefaction in the NMSZ extending from Memphis, TN up the Mississippi River to St Louis, MO.

The cone penetration test (CPT) offers three or more continuous channels of logged readings, in comparison to the standard penetration test (SPT) conducted at 1.5 m intervals in soil borings, in order to profile the subsurface strata and detect loose sands to silty sands that may be subject to liquefaction. Normalized penetration readings from both the SPT and CPT can be used for evaluating liquefaction potential [6]. In the CPT, geophones can be placed within the penetrometer to allow measurements of downhole shear wave velocities for site amplification analysis, as well as liquefaction studies.

Several series of CPT tests were conducted for mapping seismic hazards and soil properties in the NMSZ. At several locations, field CPT programs have been completed at paleoliquefaction sites previously mapped by researchers with M. Tuttle and Associates, the US Geological Survey (USGS), and the Center for Earthquake and Information (CERI), as detailed elsewhere [7,8]. Fig. 1 shows selected NMSZ paleoliquefaction sites of the current testing

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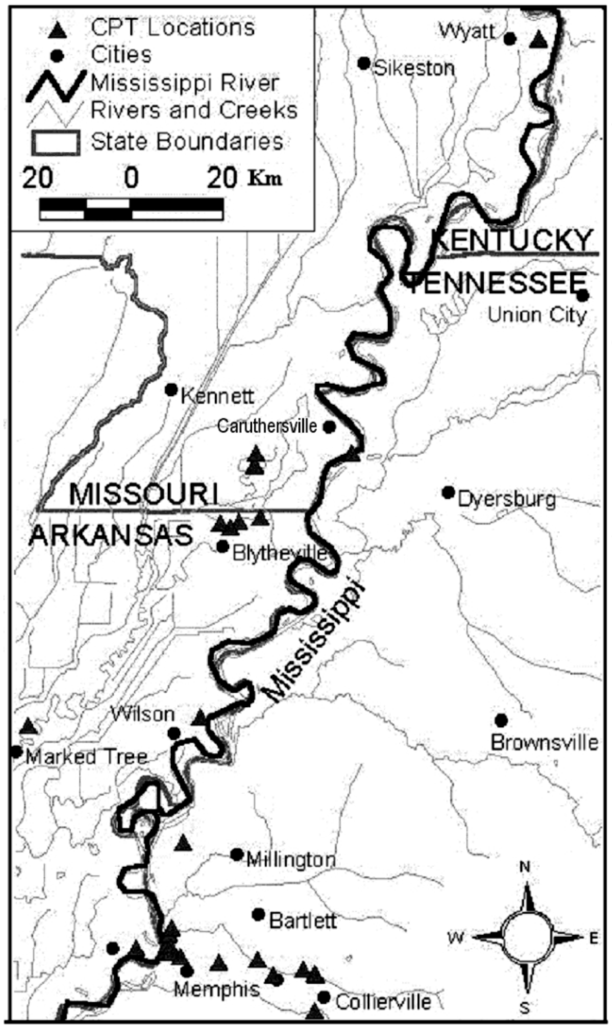

Fig. 1. Representative CPT locations in New Madrid seismic zone.

program, including the Walker Site in Marked Tree, AR, the Yarbro and Haynes sites in Blytheville, AR, and the Wolf River in Memphis, TN, and Caruthersville, MO [9]. The collected CPT data have been used for site characterization and liquefaction evaluation of the subsurface materials, as well as to investigate the causes and sizes of the observed liquefaction features (e.g. large sand blows 5–30 m in diameter; large dikes, sills, subsidence). Relative sizes of such features between nearby and adjacent liquefaction sites depend not only on the sand type, its relative density, and inplace consistency, but also on the thickness and condition of the overlying clay–silt cap, groundwater conditions, and other factors.

2. Cone penetration tests

The cone penetrometer system used in these tests included an anchored truck-mounted hydraulic rig with field computer data acquisition and three geophysics-type penetrometers (5-, 10-, and 15-ton capacity). Each penetrometer consists of a 60° angled apex at the tip instrumented to measure five independent readings: tip resistance (q_c), sleeve friction (f_s), vertical inclination (i), penetration porewater pressure (either midface u_1 or shoulder u_2), and downhole shear wave velocity (V_s). Shear waves are recorded at 1-m depth intervals, whereas the other readings are obtained at a constant logging rate, generally set between 1 and 5 cm/s.

The tip resistance (q_c) is a point stress related to the soil strength and the reading must be corrected for porewater pressure effects on unequal areas [10], especially in clays and silts. The corrected value is termed q_T. The sleeve resistance relates to the interface friction between the penetrometer and soil. Magnitudes of porewater pressure depend upon the permeability of the medium and the shoulder filter element (or u_2 position) is required for the tip correction [11]. The tip resistance (q_T), sleeve friction (f_s) and pore pressure (u_2) are used together to characterize the subsurface layering, soil behavioral type, and strength properties [10]. Particularly important in seismic investigations, a cyclic stress-based analysis of liquefaction-prone sediments is available using the q_T data [6–8,12].

The seismic piezocone test (SCPTu) includes both penetration readings and downhole geophysical measurements in the same sounding, thus optimizing data collection at a given location. Results from a representative SCPTu sounding performed along the Wolf River in northeastern Memphis, TN are shown in Fig. 2. In the test procedure, the shear waves are generated by striking a horizontal steel plank that is coupled to the ground under an outrigger. The downhole geophone is oriented parallel to the plank to detect vertically propagating, horizontally polarized shear waves. From the measured wave train at each depth, a pseudo-interval shear wave velocity (V_s) is determined as the difference in travel distance between any two successive events divided by the difference in travel times [13]. The travel times are determined in two ways: (1) by visually inspecting the recorded wave traces and subjectively identifying the first arrival, and (2) by a rigorous post-processing technique known as cross-correlation to determine the time shift between the entire wave trains from successive paired records [14].

The shear wave velocities are useful for subsequent site amplification studies, as well as the evaluation of soil resistance to liquefaction susceptibility [15]. Notably, the SCPTu is versatile as it provides both large-strain penetration test data and small-strain shear wave velocity measurements in a single sounding.

3. Soil classification

As no soil samples are obtained during the CPT, indirect methods of assessing the soil type are required. For most cases, simple ‘rules of thumb’ are sufficient: sands exhibit $q_T > 30$ atm ($1 \text{ atm} = 100$ kPa) and clays $q_T < 20$ atm. Also, for sands, the $u_2 \approx u_0$, whereas for intact clays

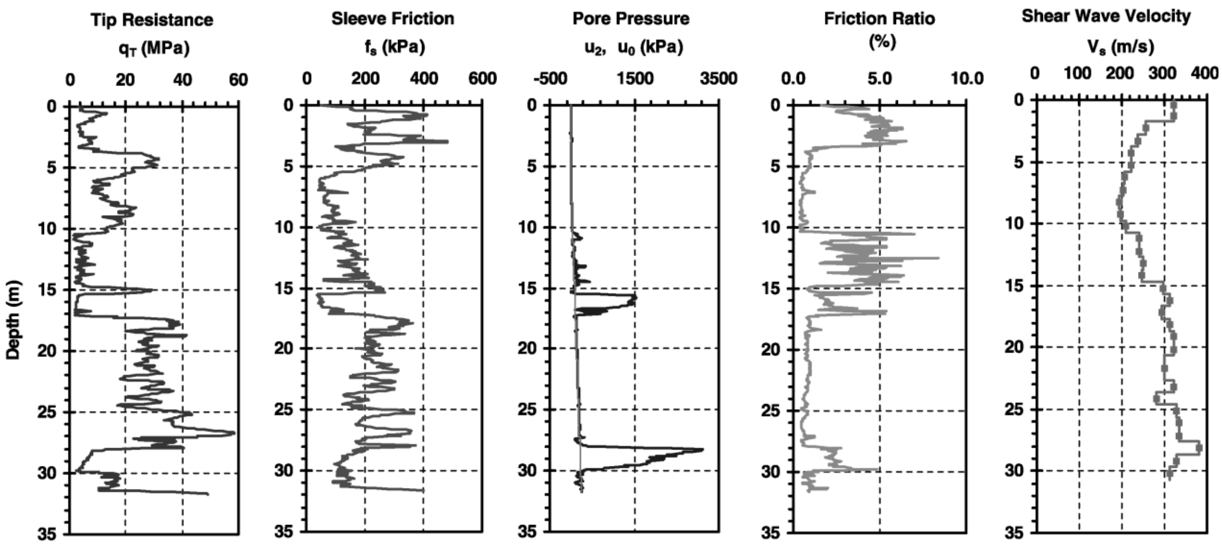

Fig. 2. Representative SCPTu sounding performed along Wolf River in Memphis, TN.

$u_2 \gg u_0$, where u_0 is the static porewater pressure. As a consequence, the measured and corrected tip stresses in sand are essentially the same value ($q_T = q_c$).

In a more systematic or automated manner, a soil profile can be generated using either soil behavior classification charts or clustering methods. The soil behavioral charts [16] are based on tip resistance (q_T), friction ratio ($FR = f_s/q_T$), and porewater pressure ratio $B_q = (u_2 - u_0)/(q_T - \sigma_{v0})$, where σ_{v0} is the total vertical stress. Another well-adopted chart is based on the normalized parameters $Q = (q_T - \sigma_{v0})/\sigma'_{v0}$, $F = f_s/(q_T - \sigma_{v0})$, and B_q [17]. An alternative approach is the use of statistical cluster analysis that can be used to analyze the stratigraphic vertical profile of sediments [18]. It detects the inherent similarity between data sets and then groups them together. Since piezocone soundings provide thousands of data points, it is often overwhelming to determine soil layering from simple visual examination and routine data processing such as spreadsheets. Clustering assists in a rational grouping of the data to define strata boundaries.

4. Liquefaction evaluation

In liquefaction analyses, the level of ground shaking from seismic loading is expressed in terms of the cyclic stress ratio (CSR). For the conventional simplified procedures, the CSR is expressed as [19]:

$$\mathrm{CSR} = \frac{\tau_{\mathrm{ave}}}{\sigma'_{v0}} = 0.65\left(\frac{a_{\max}}{g}\right)\left(\frac{\sigma_{v0}}{\sigma'_{v0}}\right)r_d \tag{1}$$

where τ_{ave} is the average equivalent uniform shear stress generated by the earthquake assumed to be 65% of the maximum induced stress, $a_{\max}$ is the peak ground acceleration (PGA) in the same unit as g, g is the gravitational acceleration constant ($g = 9.8\ \mathrm{m/s^2}$), σ_{v0} and σ'_{v0} are the total and effective vertical stresses, respectively, and r_d is a stress reduction coefficient that accounts for the flexibility of the model soil column. In this paper, the r_d recommendations of the NCEER Workshop on Evaluation of Liquefaction Resistance of Soils [12] were followed. The value $a_{\max}$ is taken from the appropriate design events for a given project (i.e. the 2, 5, or 10% probability earthquake for a certain period of time; the maximum credible event for a known fault located a certain distance from the site; or a code-based response spectrum).

The cyclic resistance ratio (CRR) is the threshold for liquefaction and used to compare the available soil resistance with level of ground shaking represented by the CSR. Therefore, if the CSR value is higher than the CRR, the soil will likely liquefy; otherwise, it will not. The CRR can be evaluated using the conventional deterministic approaches, or alternatively, the probabilistic curves of increasing likelihoods of liquefaction.

Deterministic approaches include procedures based on normalized tip resistance [6,12,15] and/or normalized shear wave velocity [8,12,15]. For the tip resistance-based method shown in Fig. 3, the cone tip resistance is normalized as a function of the effective stress (actual normalization criteria depends upon the CPT soil classification) and is designated q_{c1N}. For clean quartz sands, $q_{c1N} = q_T/(\sigma'_{v0})^{0.5}$, where the tip resistance (q_T) and effective overburden stress (σ'_{v0}) are both in atm. For silty sands, the stress-normalized cone tip resistance q_{c1N} is modified to the adjusted tip resistance $(q_{c1N})_{cs}$, which is its equivalent clean sand value, by the relationship $(q_{c1N})_{cs} = K_c q_{c1N}$, where K_c is the correction factor for the apparent fines content and is empirically calculated from the CPT Q and F data. For clean sands, $(q_{c1N})_{cs} = q_{c1N}$. The level of ground motion (CSR) and the adjusted tip resistance $(q_{c1N})_{cs}$ are compared with the cyclic resistance (CRR) to determine whether liquefaction will or

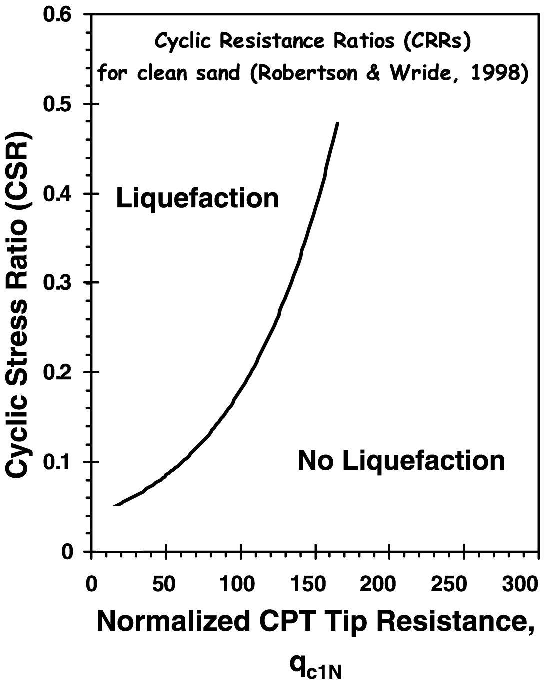

Fig. 3. Deterministic approach for liquefaction analysis of clean sand based on tip resistance. After Robertson and Wride [20].

will not occur. The CRR for clean sand is calculated by the following equation for an earthquake moment-magnitude of 7.5 [12,20]:

$$\mathrm{CRR}_{7.5} = 93((q_{\mathrm{c1N}})_{\mathrm{cs}}/1000)^3 + 0.08,\ \text{if}\ 50 \le (q_{\mathrm{c1N}})_{\mathrm{cs}} < 160$$

$$\mathrm{CRR}_{7.5} = 0.833((q_{\mathrm{c1N}})_{\mathrm{cs}}/1000) + 0.05,\ \text{if}\ (q_{\mathrm{c1N}})_{\mathrm{cs}} < 50 \qquad (2)$$

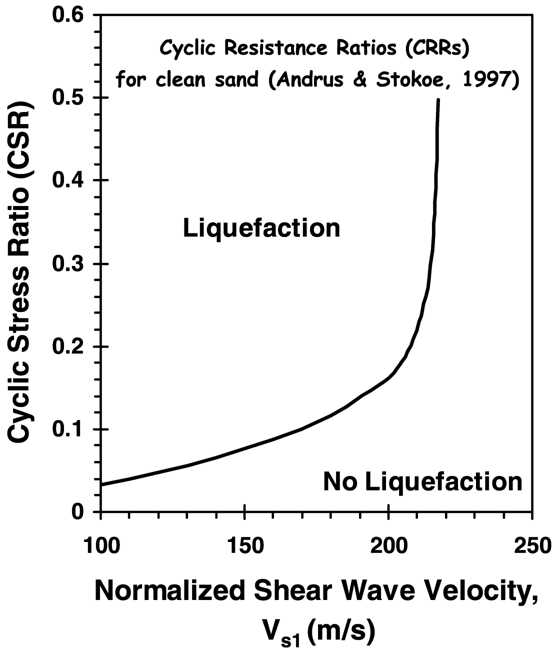

Fig. 4. Deterministic approach for liquefaction analysis of clean sand based on shear wave velocity. After Andrus and Stokoe [15].

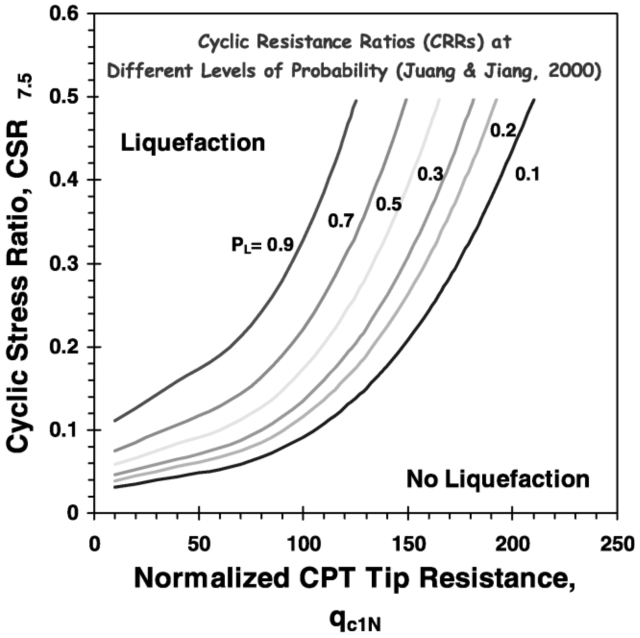

Fig. 5. Cyclic resistance ratios (CRRs) based on tip resistance at different levels of probability. After Juang and Jiang [22].

For liquefaction evaluation based on shear wave velocity, a deterministic chart procedure is shown in Fig. 4. Here, the shear wave velocity is stress-normalized to $V_{\mathrm{s1}} = V_{\mathrm{s}}/(\sigma'_{\mathrm{v0}})^{0.25}$, where V_{s} is in m/s and σ'_{v0} in atm. The CRR for an earthquake moment-magnitude of 7.5 is found from [12,15]:

$$\mathrm{CRR}_{7.5} = a(V_{\mathrm{s1}}/100)^2 + b[1/(V_{\mathrm{s1c}} - V_{\mathrm{S1}}) - 1/V_{\mathrm{s1c}}] \qquad (3)$$

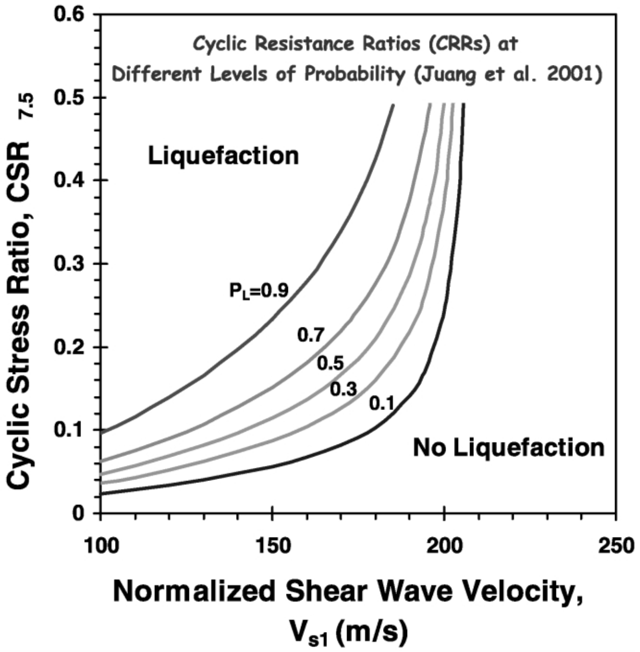

Fig. 6. Cyclic resistance ratios (CRRs) based on shear wave velocity at different levels of probability. After Juang et al. [23].

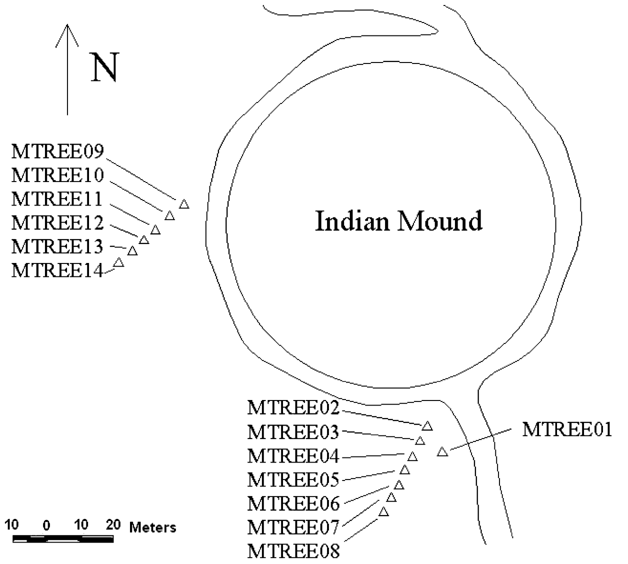

Fig. 7. Overview of the CPT locations at Marked Tree paleoliquefaction site, AR.

where $a = 0.03$, $b = 0.9$, V_{s1} is the overburden stress-normalized shear-wave velocity, and V_{s1c} is a limiting asymptote value. From statistical database analyses, Andrus and Stokoe [15] determined the following values for sands and gravels related to fines contents: $V_{s1c} = 220$ m/s for FC $\leq 5\%$; $V_{s1c} = 210$ m/s for FC = 20%; and $V_{s1c} = 200$ m/s for FC $\geq 35\%$.

Deterministic methods give only a binary evaluation of liquefaction potential. A calculated factor of safety (F_s) can be defined as $F_s = \mathrm{CRR/CSR}$ for a particular earthquake magnitude and set of data. In more recent evaluations, CRR curves of different probabilities of occurrence have been developed from the original databases.

Based on the normalized tip resistance, a mapping function was proposed [21,22] to relate the safety factor F_s to the liquefaction probability P_L based on a database of 225 CPT-based cases reported by Juang and Jiang [22]:

$$P_L = 1/[1 + (F_s/1.0)^{3.34}] \tag{4}$$

Based on the shear wave velocity, there is a similar mapping function [23]:

$$P_L = 1/[1 + (F_s/0.72)^{3.1}] \tag{5}$$

The CSR is calculated according to Eq. (1), and the CRR is determined from Eq. (2) if it is based on the tip resistance, or from Eq. (3) if it is based on the shear wave velocity. Curves of CRR for different probabilities of liquefaction based on normalized tip resistance are shown in Fig. 5. This provides a more rational means of assessing the likelihood of liquefaction for a particular CSR and soil resistance measured by q_{c1N}. The CRR curves at different probabilities ranging from 10 to 90% are given in Fig. 6 for normalized shear wave velocity, V_{s1}.

5. CPT tests performed in Marked Tree, AR

A series of CPT tests was performed at the Walker paleoliquefaction site that is located near Marked Tree, AR. This site was selected for a paleoseismology study because sand blows were found in association with a Native American occupation horizon, suggesting that the sand blow was prehistoric in age [24]. The study included a large scale surface resistivity survey to locate anomalies indicating the exact location of the feeder dikes [25], followed by excavation and documentation of the liquefaction features and the cultural horizon [9]. On the basis of radiocarbon dating and artifact analysis, the sand blows and related dikes are thought to have formed during a large New Madrid earthquake circa A.D. 1450 [24,26]. Although the full extent of the A.D. 1450 liquefaction field has not yet

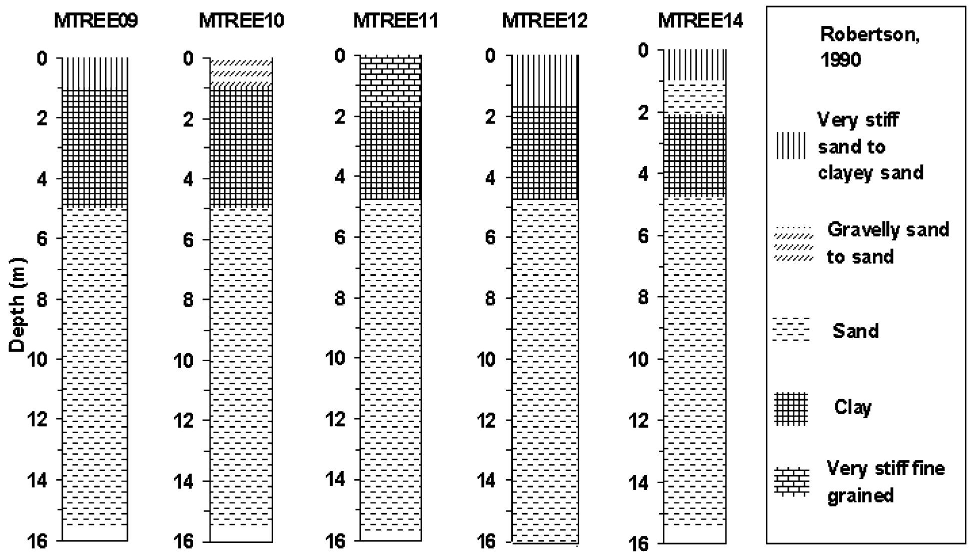

Fig. 8. Interpreteted soil stratigraphy of the second series of soundings using clustering and CPT soil behavioral charts.

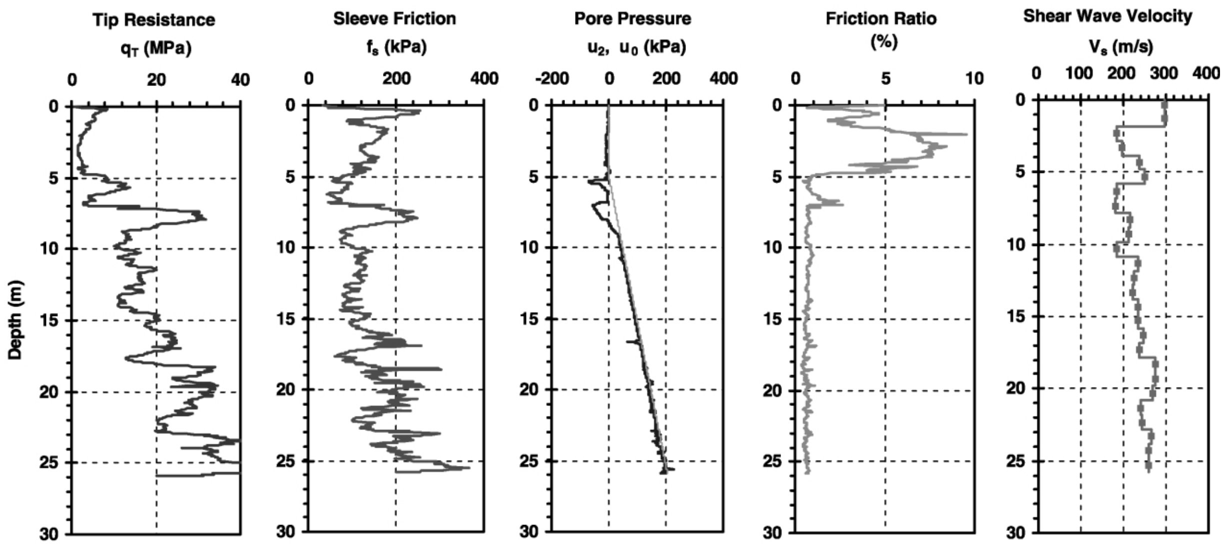

Fig. 9. Representative seismic piezocone results at Walker paleoliquefaction site near Marked Tree, AR (sounding MTREE12).

been determined, this is the southernmost known occurrence of sand blows of this age. At a later date (August 2000), the CPT testing was performed in two linear arrays perpendicular to the main direction of the sand dikes, as shown by Fig. 7. The intention of these series was to provide information on the subsurface stratigraphy and source sands, explore lateral variability, and evaluate the potential for re-liquefaction. The soil profiles for the second array of soundings have been evaluated according to the soil behavioral chart [17] and cluster analysis [18], as shown in Fig. 8. It can be seen that the profiles mainly consist of clay and silt for the upper 5 m. The remainder of the profiles to depths of at least 16 m indicates the presence of sand that may be prone to liquefaction during a similar large earthquake event.

Results from a representative seismic piezocone sounding (No. MTREE12) advanced to a depth of 26 m at the Walker site are shown in Fig. 9. The readings indicate a clayey layer in the upper 5 m underlain by an extensive deposit of relatively clean sands with varying facies. The profile corresponds similarly with the boring and geological log of a nearby site reported by Liu et al. [27]. Since the Walker Site is a well-documented paleoliquefaction site, an earthquake magnitude of 8.0 has been used for the liquefaction analysis. Fig. 10 shows the results of liquefaction analysis for the sounding MTREE12 by

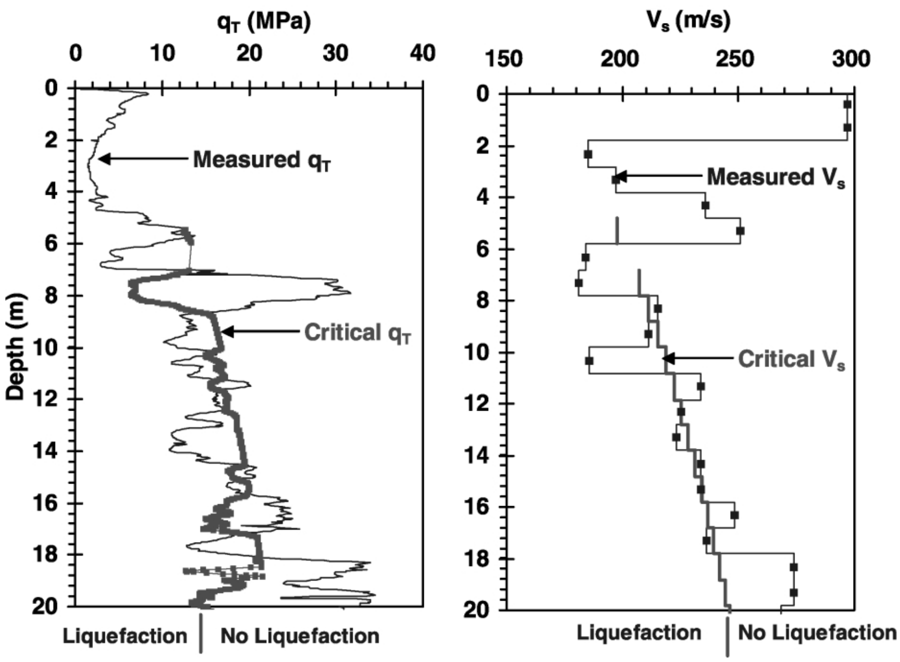

Fig. 10. Liquefaction analyses by deterministic approaches for Marked Tree sounding.

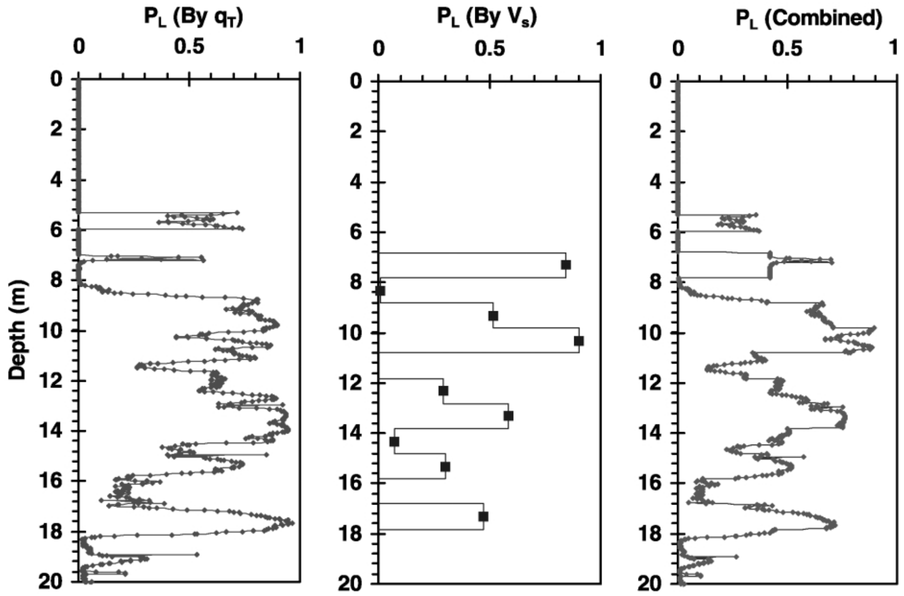

Fig. 11. Liquefaction analyses by probabilistic approaches for Marked Tree sounding.

the deterministic approach. At a factor of safety of $F_s = 1.0$ for liquefaction, the critical values of tip resistance and shear wave velocity are derived by inversing the process of calculating CRR. This critical value, which changes with depth, is shown in the same graph as the measured value in the figure. Liquefaction is likely whenever the measured value is less than the critical value. The gaps in the critical value data represent soil layers that are not susceptible to liquefaction due to their classification (e.g. clayey soils for which liquefaction analyses are not relevant).

Similarly, the CRR probability curves can be applied to the CPT data from the Walker paleoliquefaction site. The probabilistic procedure is presented as the different liquefaction probabilities versus the corresponding depth in Fig. 11. The probability is analyzed based on the independent critical tip stress and the shear wave velocity, respectively, as well as jointly. The combined probability can be calculated as the average of the probabilities based on the two approaches. From the combined liquefaction probability shown in Fig. 11, it can be seen that the region from 9 to 11 m is most susceptible to liquefaction, and at selected other depths, e.g. from 7 to 8 m, from 12 to 14 m, and from 17 to 18 m, the soils also have a high probability of liquefying under an earthquake magnitude of 8.0. Other magnitude events can also be investigated with this technique. This analysis reflects the liquefaction potential of the sediments at the site today and does not try to back-calculate the magnitude of the A.D. 1450 earthquake that produced the liquefaction features.

In future research efforts, an improved procedure would be obtained by adopting a similar CRR form for both the normalized cone tip resistance and shear wave velocities. Consistency and a better compatibility of results would be expected. A joint-probability curve based on $(q_{c1N})_{cs}$ and V_{s1} could also be developed from statistical analyses.

6. Conclusions

Geotechnical site characterization using CPT in the NMSZ serves multiple purposes, including (1) identifying soils with high potential to liquefaction; (2) providing data for site amplification analysis; and (3) obtaining information for ongoing paleoliquefaction studies. Of particular interest, the SCPTu is an efficient way to assess the liquefaction potential of soils, as it provides logging of tip stress, sleeve friction, porewater pressure, and shear wave velocity in a single sounding. These data can be processed to identify the stratigraphy, layers susceptible to liquefaction, level of ground shaking, and soil resistance to liquefaction. Deterministic and/or probabilistic curves can be used with the normalized tip resistance q_{c1N} and shear wave velocity V_{s1} in evaluating soil liquefaction potential. The redundancy information from two independent readings provides a higher level of confidence in the conclusions on liquefaction hazards.

Acknowledgments

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